REMR Technical Note CS-ES-2.8

Predicting Concrete Service Life for Cases of Freezing and Thawing Deterioration

Purpose

To describe a general procedure for predicting the service life of nonair-entrained concrete when the deterioration mechanism is freezing and thawing.

Background

A significant number of Corps mass concrete structures were built before the advent of air-entrained concrete. Since many of these structures are located in the northern regions of the country, it is not surprising that the nonair-entrained concrete has deteriorated due to freeze-thaw conditions. A procedure for predicting the service life of nonair-entrained concrete subject to damage from freezing and thawing has been developed. The procedure uses a probabilistic method to address both the known and unknown qualities of the relevant material properties, environmental factors, and model of degradation. Two important characteristics of this procedure are that (a) it rationally addresses the uncertainties inherent in degradation of mass concrete due to freezing and thawing and (b) the procedure is mathematically straightforward for implementation by Corps of Engineers (CE) offices.

Procedure

The mechanism of freezing and thawing used in this procedure is based on the thesis that damage in a unit volume occurs when the temperature is below a critical value ($\Theta < \Theta_{cr}$) and the degree of saturation (amount of freezable water) exceeds a critical value ($S > S_{cr}$). The temperature and degree of saturation vary in response to external environmental conditions as determined by the material properties. When either event occurs singly, there is no damage, but rather it is their simultaneous occurrence that causes damage. In this context, soundness of the concrete is considered a binary state process; i.e. either the unit volume is damaged or it is not.

The hazard function or instantaneous rate of failure is

$$h(t) = P(\Theta < \Theta_{cr} \cap S > S_{cr}) \qquad (1)$$

that is, the joint probability of temperature less than critical and saturation greater than critical. Although the hazard function generally is a function of time, on the scale of damage due to freezing and thawing, it is reasonable to discuss annual failure rates, λ , which are unaffected by seasonal variations. For simplicity herein, we assume that the factors which determine criticality of temperature are independent of those defining the criticality of saturation such that:

$$\lambda = P(\Theta < \Theta_{cr}) \cup P\,(S > S_{cr}) \tag{2}$$

The constant hazard function, λ , implies an exponential distribution of service life. Further, the expected service life is the reciprocal of the failure rate; i.e.,

$$T = 1/\lambda \tag{3}$$

It is obvious from Equations 2 and 3 that an increase in the probability of temperature less than critical or saturation greater than critical increases the failure rate and inversely decreases the service life. The behavior implied by these equations agrees with the observed deterioration history at typical CE concrete structures; i.e., some structures deteriorate rapidly and need early repair while others experience very slow deterioration.

The probabilistic procedure includes four basic steps prior to determination of the required probabilities of temperature and saturation criticality for the unit volume. These steps are as follow:

a. Determine critical temperature, Θ_{cr} .

b. Determine critical degree of saturation, S_{cr} .

c. Determine distribution of temperature, Θ .

d. Determine distribution of degree of saturation, S .

The critical temperature is a function of several factors which affect the freezability of water in the concrete. The impurities in the water reduce the freezing point below normal, and as any part of the water in a pore begins to freeze, the remaining part has an even lower freezing point.[1] At this time, these effects have not been quantified, so for the purposes of this study, a constant deterministic value of Θ_{cr} must be assumed.

The critical degree of saturation is determined by a number of factors not known with certainty. Critical pore size, moisture migration due to freezing, and frost-generated pressures are known to affect the critical degree of saturation. Currently, no widely accepted quantitative relationship between

[1] Assuming the water is not a saturated solution before freezing begins, as it will be if nothing is dissolved in it but calcium hydroxide.

these variables is available. Therefore, simple reasoning was used to assume that a degree of saturation less than 91 percent is not critical, based on the 90-percent expansion of water when frozen.

Temperature in a unit volume can be estimated from the environmental conditions and thermal material properties. For some simpler cases, closed-form solutions of the deterministic heat transfer equations exist. More generally, finite-element or finite-difference computer codes provide a solution. For the probabilistic analysis, we need to determine the distribution of temperature for the unit volume. In determination of this distribution, the uncertainty or randomness of the functionally independent variables in the deterministic analysis must be considered. In general, these random variables include environmental temperature Θ_e , thermal conductivity k, specific heat c_p , and material density, ρ .

Calculation of the degree of saturation experienced by a unit volume of concrete presents a more challenging problem, even in the deterministic sense. Moisture migration in concrete is generally considered to include two mechanisms: seepage and capillary action.[2] For older concrete structures, moisture migration, and thus degree of saturation, is primarily due to seepage. Seepage through permeable materials is reasonably well understood and depends primarily on the coefficient of permeability of the material and the external heads of the fluid. For the probabilistic analysis, we determine the distribution of degree of saturation for the unit volume. In determination of this distribution, the randomness of the junctionally independent variables (permeability and external head) are considered in the deterministic analysis.

The environmental data required for prediction of damage due to freezing and thawing by this procedure include air temperatures, water temperature, ground temperatures, and water levels. Each of these input random variables can be described by a probability distribution function. The data for each variable can be determined from an appropriate source for a study site and represented by its statistical parameters.

Results

This procedure was demonstrated by hindcast application to two structural features at CE Civil Works structures which exhibited an appreciable degree of measurable damage due to freezing and thawing. Required data for application of the procedure (e.g., temperature and concrete properties) were available for these features, which were representative of typical CE projects. From six candidate structures, two features were selected as case studies for application

[2] In fact, for typical concrete having any value of w/c below 0.7, there will be no capillary continuity in concrete after 1 year; at lower values continuity will be lost sooner, by 14 days for w/c = 0.5; hence moisture movement will be by surface diffusion in intact concrete.

of the procedure. These two features were the middle and land walls at Dashields Lock. Figure 1 is a drawing of the middle wall with the area of study represented by the area closed by ABCD.

The procedure was applied using the available data for each case study. One- and two-dimensional thermal analyses were used to determine the thermal response of each wall and the resulting probabilities of critical temperature. Figure 2 shows the probability of freezing contours for the area of the middle wall studied. As should be expected, the probability of freezing is zero below the waterline and for some interior portions above the waterline. The probability of freezing above the waterline is primarily driven by the reduction temperature amplitude with increasing depth.

Simplified seepage analyses provided the probabilities of critical saturation which are shown in Figure 3. For this study, the degree of saturation was considered critical below the phreatic surface and not critical above. It was assumed that the water levels on each side of the middle wall have the same probability distribution, and thus the location of the phreatic surface and critical saturation have the same probability distribution as the water level.

The annual probability of damage (Figure 4) and the predicted service life (Figure 5) were determined from the joint probabilities of critical temperature and critical saturation throughout the structure. The area of highest damage is just above the waterline where the service life is predicted to be only 15 years at a depth of 9 in. At 2 ft, the service life is predicted to be about 40 years; at 3 ft, 100 years. This service life prediction is encouragingly similar to the observed deterioration on the middle wall at Dashields.

Reference

Bryant, L. M., and Mlakar, P.F. (1991). "Predicting concrete service life in cases of deterioration due to freezing and thawing," Technical Report REMR-CS-35, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

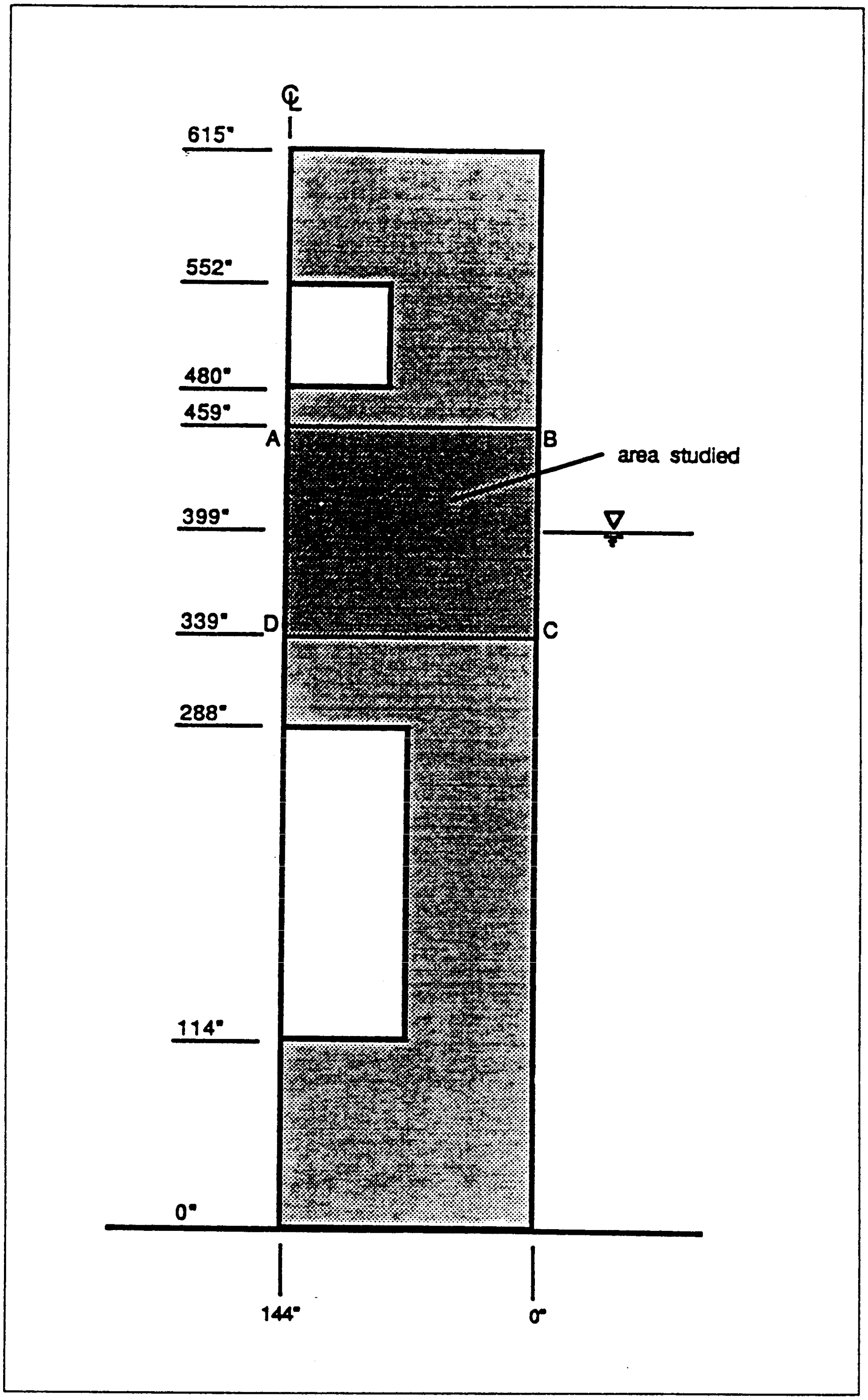

Figure 1. Area of middle wall studied in more detail

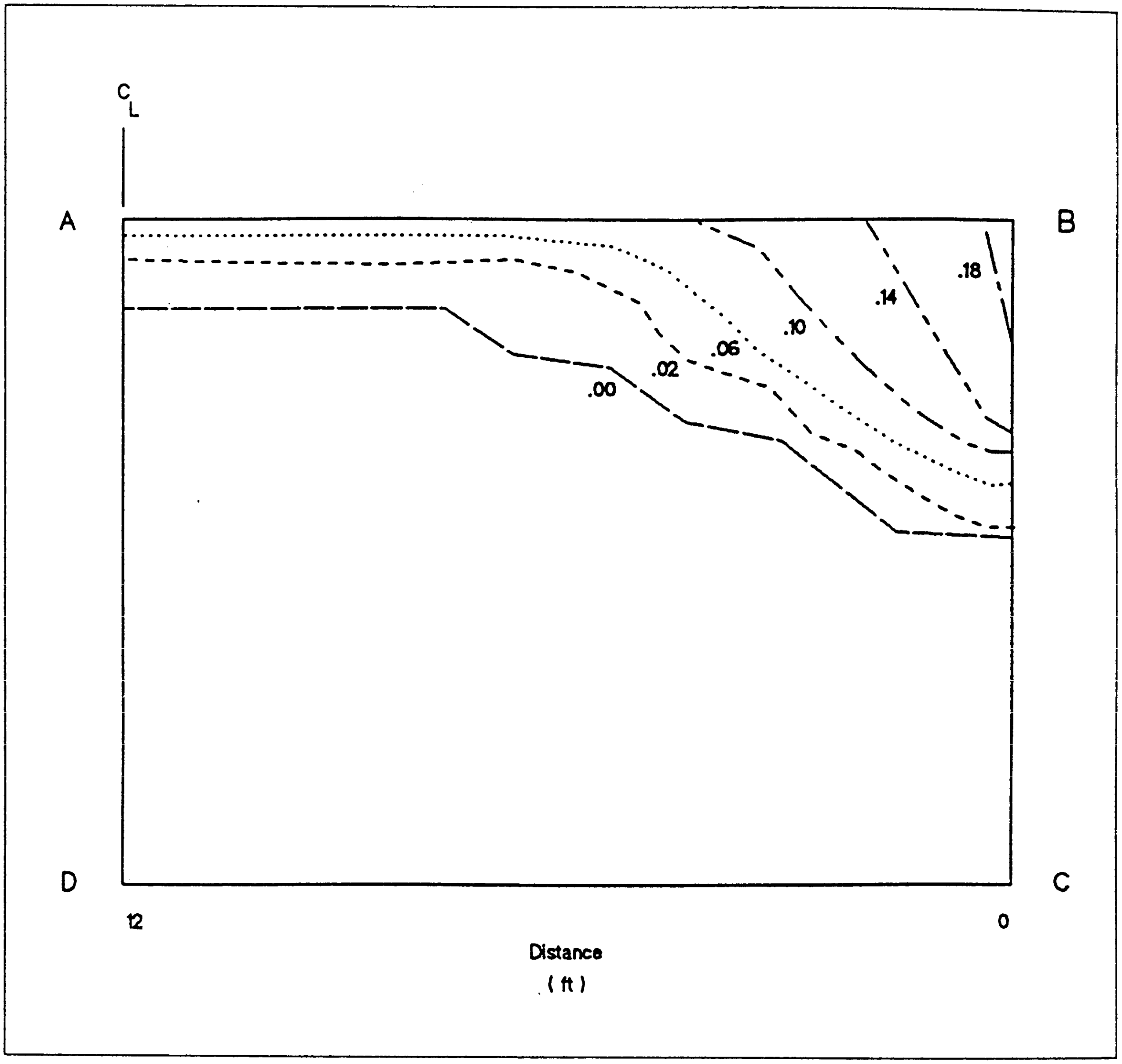

Figure 2. Probability of freezing in middle wall

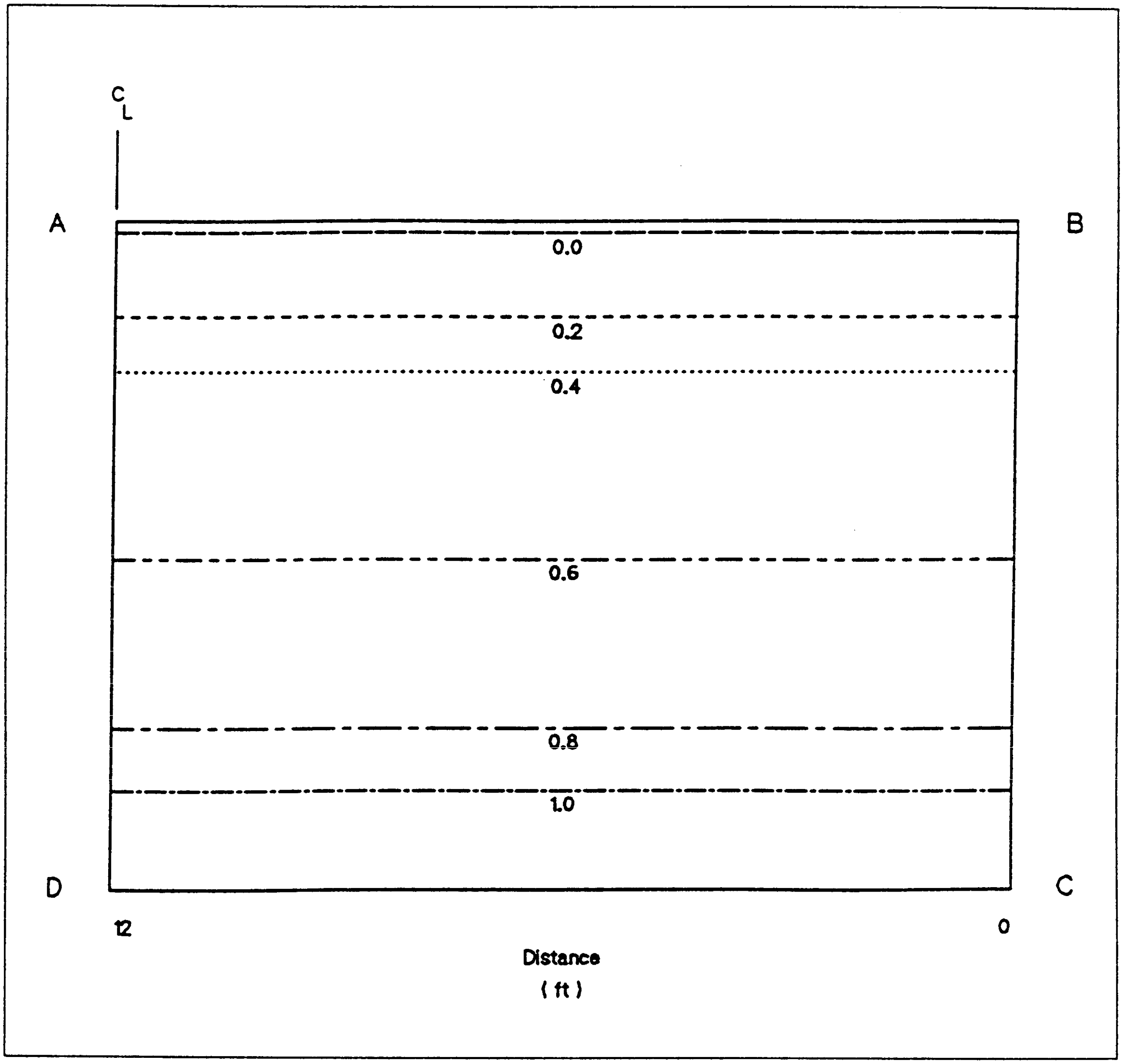

Figure 3. Probability of critical saturation in middle wall

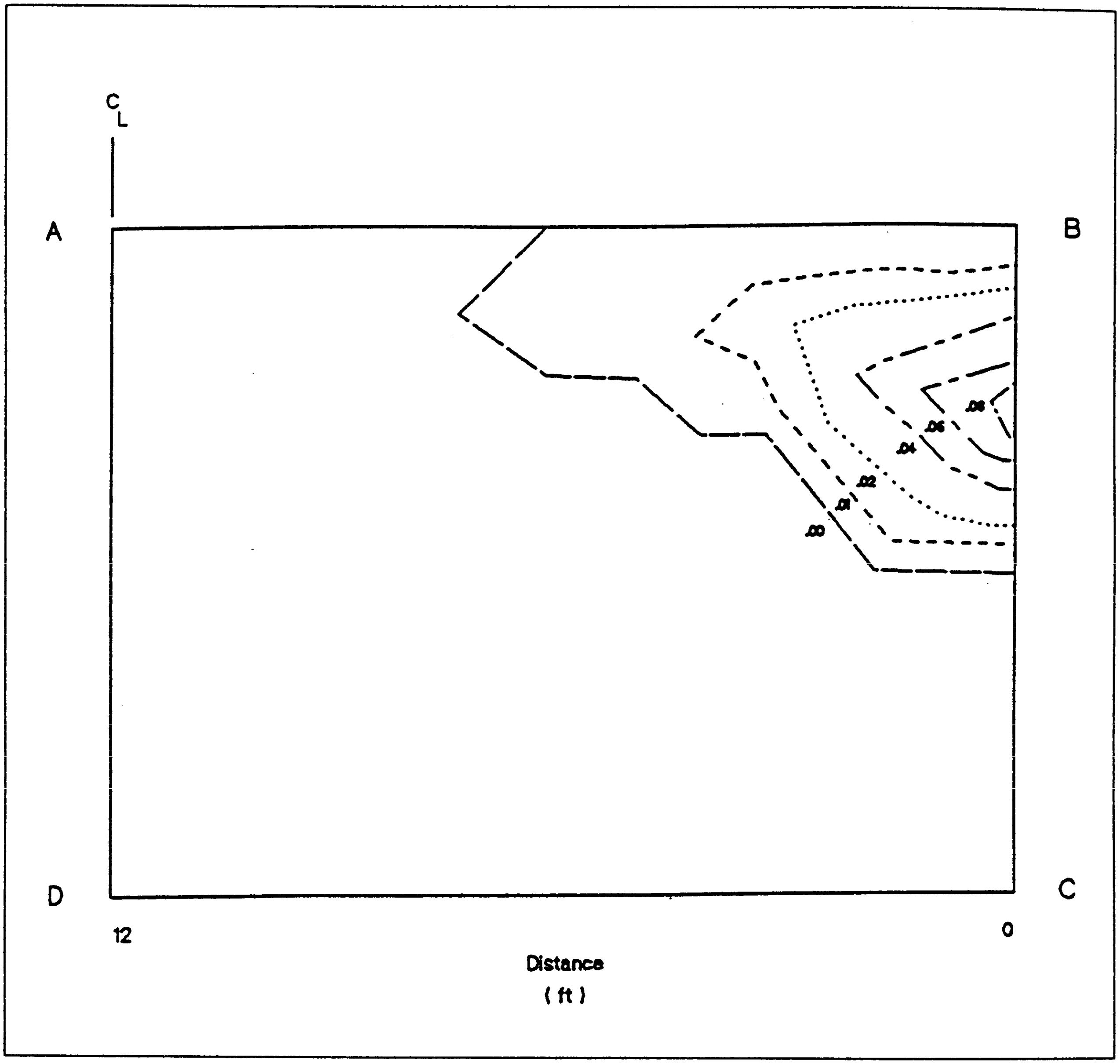

Figure 4. Annual probability of damage for middle wall at Dashields Lock

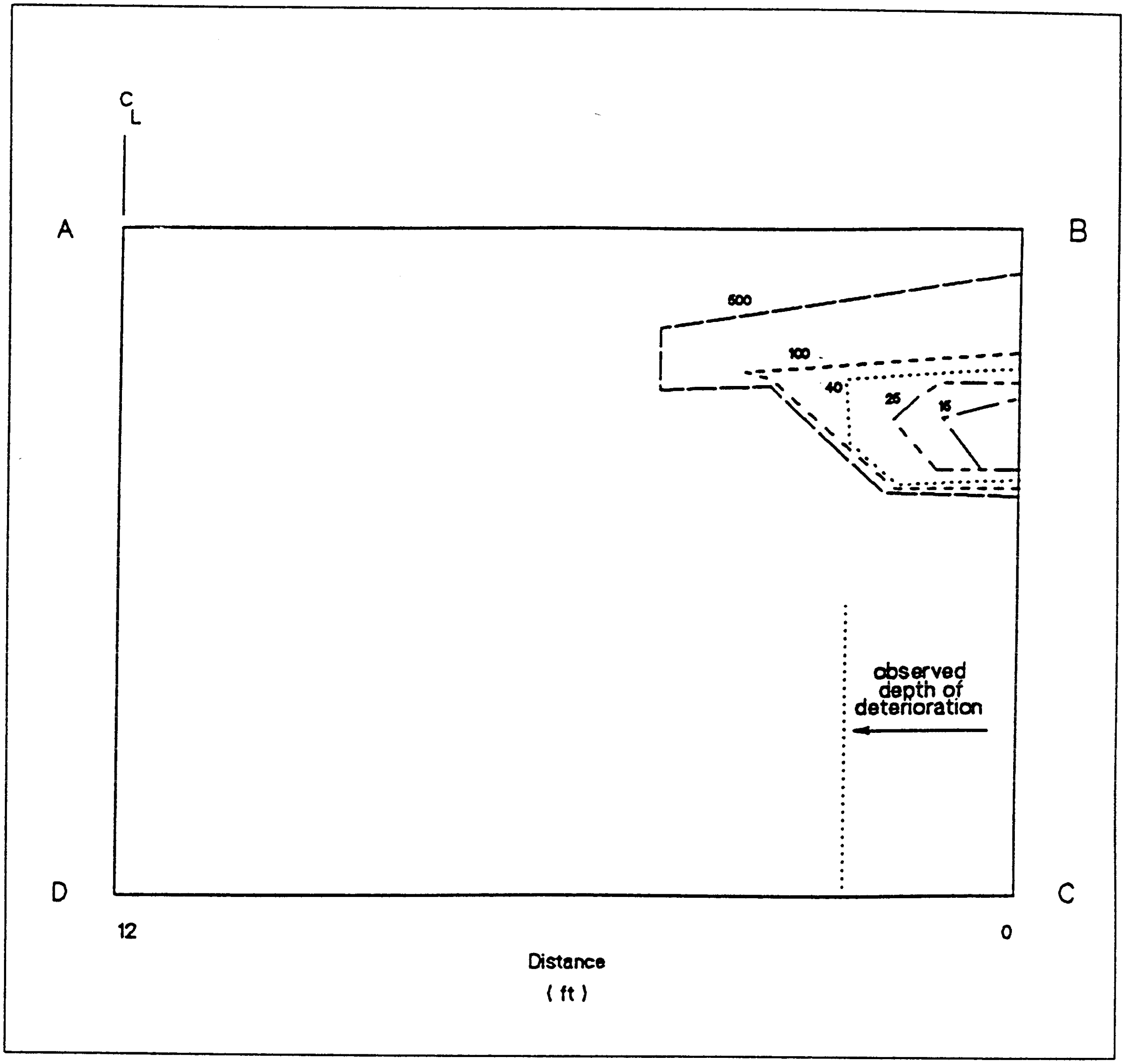

Figure 5. Service life (years) prediction for middle wall at Dashields Lock